ULTRASONIC NDE OF THREE-DIMENSIONAL TEXTILE COMPOSITES

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INTRODUCTION

Composite materials represent the future of the defense, transportation and civil construction industries. These materials have been used extensively in recent years on applications varying from tennis rackets to re-entry vehicles. Modern applications are requiring more complex geometries, and more large scale unitized composite structures. These applications are presently not feasible due to the high manufacturing cost and two-dimensional nature of conventional composite materials.

Three-dimensionally reinforced preforms, which can be woven dry and later infiltrated via resin transfer molding or similar processes, offer a potential solution to both of these limitations. These materials offer through-the-thickness reinforcement which greatly enhances the out-of-plane strength and damage tolerance [1,2]. However, improvements in through-the-thickness strength come at the expense of in-plane stiffness and strength, particularly in compression [3,4]. Reductions of in-plane properties are primarily attributed to a decrease in in-plane fiber volume due to the presence of the out-of-plane reinforcement, fiber breakage of in-plane fiber bundles due to the introduction of the reinforcing fibers, misalignment or waviness of in-plane fibers due to the presence of the reinforcing fibers, and resin rich areas caused by the reinforcing mechanism and the ensuing fiber matrix disbond. A greater understanding of the mechanics of the three-dimensional fiber architecture will allow greater control of these parameters, and thus minimize the reduction of in-plane properties. For this reason, a project has been initiated to investigate the mechanical response of multi-directionally reinforced composite materials.

This paper addresses an investigation into the increased challenges associated with locating, identifying and characterizing flaws in three-dimensional fiber architectures. We will focus on the applicability of non-destructive ultrasonic inspections for quality assessments in various three-dimensional textile fiber architectures. These assessments will include a determination of typical flaws expected in such composites. We will address methods being pursued to characterize the severity of fiber architecture flaws within a laminate. Finally, we will address related activities including fabrication of idealized textile composites to illustrate specific combinations of textile fiber architecture, and mechanical testing to identify critical parameters for mechanical performance which should be looked for in nondestructive inspections.

DESCRIPTION OF SPECIMENS

Samples which have been investigated in this study include through-the-thickness and layer-to-layer angle interlocks, 3D braids, 3D orthogonal weaves and 5-directional weaves. Representative textile architectures are shown in Figure 1. Variations of these architectures which were investigated include tow size (both in-plane and out-of-plane) and interlock angle (the slope of the through-the-thickness fiber in the idealized architecture). Of primary importance is the realization that Figure 1 illustrates the idealized architecture. Physical constraints often dictate particular details not shown in these idealizations, such as

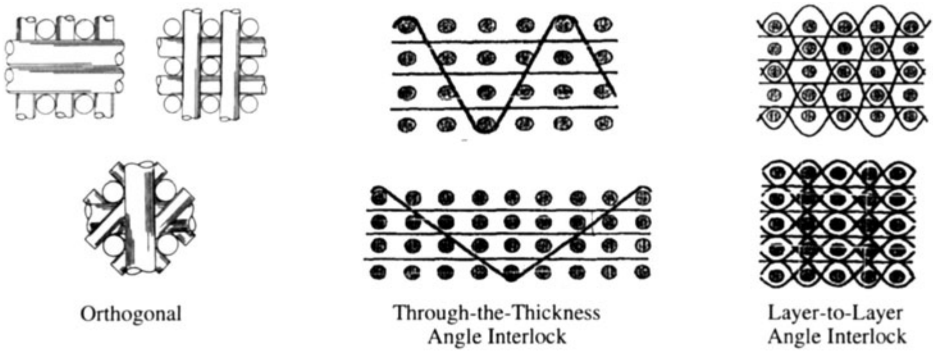


Figure 1. Representative idealized three-dimensional fiber architecture.

placement of continuous through-the-thickness fibers in orthogonal weaves requiring loops at the surface or periodic travels along the surface which distort the local in-plane fiber alignment (Figure 2). Furthermore, during compaction and cure the actual fiber architecture is often significantly distorted, such as shown in Figure 3. These details can have significant influence on mechanical performance, and thus should be identified in nondestructive evaluations. The difficulty lies in the random nature in which these distortions can occur. Identical weaves may behave quite differently after curing due to variations in fiber architecture distortions. This makes the task of qualifying these materials very difficult, as the scatter in mechanical data is likely to be severe. Nondestructive evaluations have the potential for identifying the severity of fiber architecture distortion, and thus could be used to normalize test data to reduce scatter. In the same manner, these inspections could be used in industry to quantify the expected mechanical performance knockdown from the idealized architecture performance based upon the severity of the fiber architecture distortion.

INSPECTION -- ORTHOGONAL WEAVES

Orthogonal weaves have been identified as particularly difficult to inspect due to an interesting phenomenon which occurs in the propagating wave. The incident energy pulse is separated into two distinct signals -- one which propagates along the through-the-thickness fiber bundle and one which travels transverse to the in-plane fiber bundle. Since the velocity of propagation along the fiber is significantly greater than that transverse to the fiber, two distinct back surface reflection signals or through-transmission signals are detected, as the case may be. Complications this presents and recommended solutions have been addressed previously [5], however we note here that this has been further verified on additional orthogonal samples with the same results. In all cases two signals are detected,

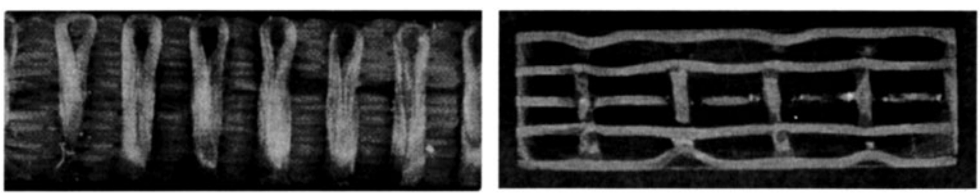


Figure 2. Typical fiber architecture details not accounted for in idealized sketches.

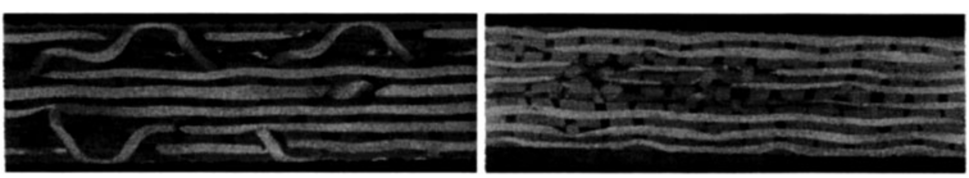


Figure 3. As-cured fiber architecture demonstrates typical distortions.

and the signal transverse to the in-plane fibers is useful for locating flaws such as porosity and microcracking.

As an illustration, Figure 4 shows scans for two different orthogonal samples. The scan for sample 24-PH-4 illustrates the ability to detect significant flaws using only the signal transverse to the in-plane fibers -- flaws which were not detected using a single back surface gate covering both signals. Note that sample 23-PH-3 was fabricated using 6k tow, and has a unit cell size of 0.14", whereas sample 24-PH-4 was fabricated using 3k tow and has a unit cell size of 0.06". A common flaw in orthogonal weaves appears to be the existence of significant matrix cracking. This flaw has, to some extent, been observed in every orthogonal sample investigated in this study. The difference between the two scans shown occurs because the microcracking in sample 23-PH-3 is far less severe than that for sample 24-PH-4 (Figure 5). Note that for both samples microcracking appears to initiate in the "crown" region where the through-the-thickness fiber bundle loops near the surface. For the larger unit cell size, cracks propagate parallel to the through-the-thickness fiber and thus are not detected in a conventional normal incidence inspection. For the smaller unit cell size, cracks propagate in more random directions, often growing together. Further-

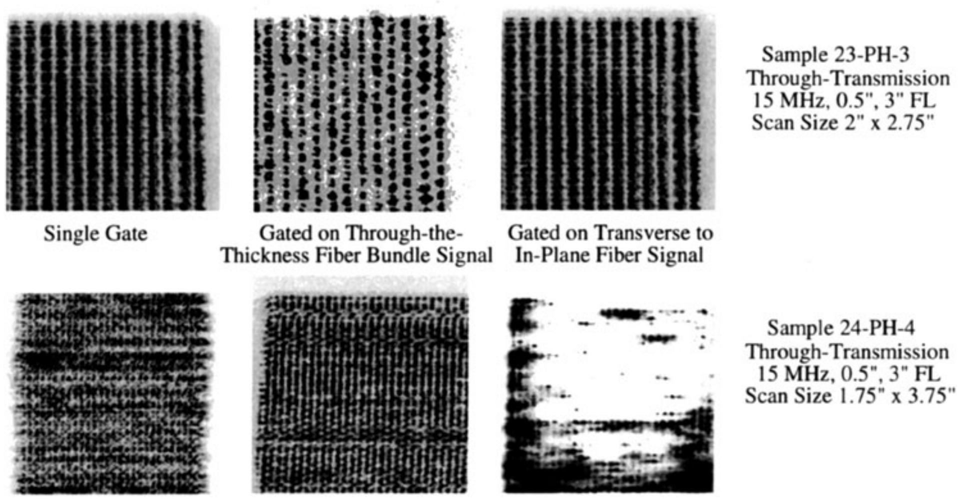


Figure 4. Orthogonal samples verify dual signal inspection techniques.

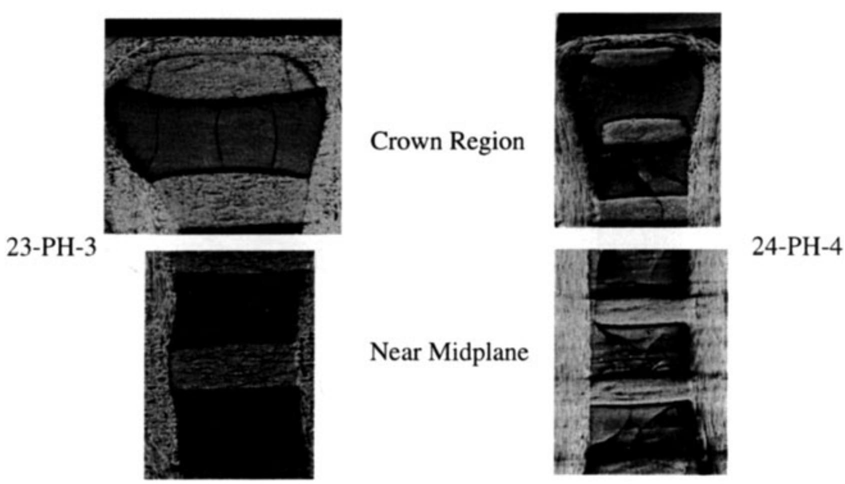


Figure 5. Severity of microcracking in orthogonal weaves depends on geometry.

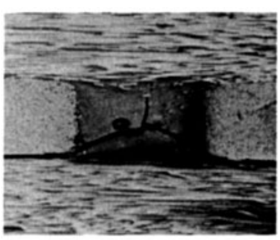
more, for a large area of the composite investigated tight cracks propagating from the two surfaces along the through-the-thickness fiber bundle have met at the centerline and traveled orthogonally along the in-plane fibers (Figure 6). Thus the normal incidence through-transmission inspection using only the signal transverse to the in-plane fibers shows a large region with no signal. The inspection using a single gate is ambiguous, because even though no signal is transmitted transverse to the in-plane fibers, energy is still transmitted along the intact and closely spaced through-the-thickness fiber bundles.

As a final note to the characterization of orthogonal weaves, note that the concept of attenuation measurement is not valid for these more complex fiber architectures. The fiber architecture acts similar to a diffraction grating for the incident energy. Furthermore, separation of this incident energy into two distinct waveforms makes it such that comparison with a reference signal is not practical without some means of determining the amounts of energy which go into each transmitted signal. Preliminary "attenuation" data [5] for the samples previously addressed show accurate trends, but should be viewed in terms of the energy separation just described. This is particularly true for the attenuation of the signal along the through-the-thickness fiber. This attenuation should be quite low, as there should be low losses along the fiber direction. However, the associated signal is quite small due to the small cross-sectional area percentage of the through-the-thickness fiber bundles.

INSPECTION -- INTERLOCKS AND BRAIDS

Traditional methods of inspection have proven to be effective for three-dimensional weaves which do not have orthogonal fiber arrangements. These methods, however, will not be as successful as for traditional two-dimensional layered composites (material with no through-the-thickness reinforcement) due to complications introduced by the textile pattern. Of particular relevance is the predominance of the textile pattern in the C-scan images. Figure 7 is a representative C-scan image for a three-dimensional textile. Note the repeating pattern indicative of the textile architecture. This pattern clearly illustrates the in-plane fiber misalignment which was likely caused by the flow of resin in the resin transfer molding process. The time of flight map indicates the thickness variation which the panel exhibits. However, the predominance of the textile pattern makes subtle backgound variations due to local porosity or inclusions difficult to identify. Experiments involving introducing a series of flat bottomed holes are presently underway to characterize the sizes of flaws which might be detectable in a variety of weave architectures.

An equally interesting phenomenon results from an almost opposing effect -- that is a seemingly major flaw which is merely a deviation in the fiber arrangement. Figure 8 shows such a deviation. Again, the textile pattern is evident, but the strong vertical bands would seem to indicate the existence of broken bands of fibers, resin rich regions, or cracked regions. Instead, these regions are seen to be areas of severe fiber undulation in two adjacent layers, resulting in significant scattering (wave coupling, reflection and refraction) of the ultrasonic energy. This method of detecting and characterizing "waves", referred to here as out-of-plane undulations in the fiber architecture, has been utilized on two-dimensional composites with localized waves, and will be discussed later in this paper. This type of ultrasonic response could lead to misinterpretation of the data.



1 cm = 130.6 μm

1 cm = 65.9 μm

Figure 6. Cracks propagate into midplane delamination in sample 24-PH-4.

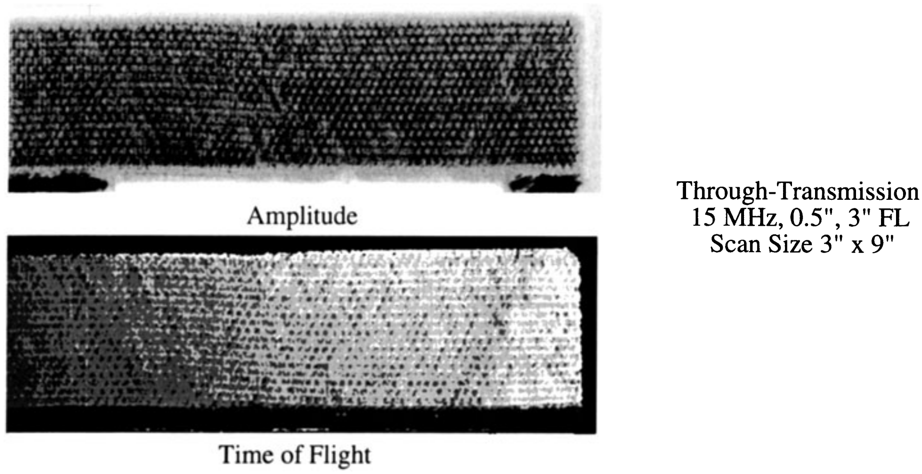


Figure 7. Representative 3D textile C-scan.

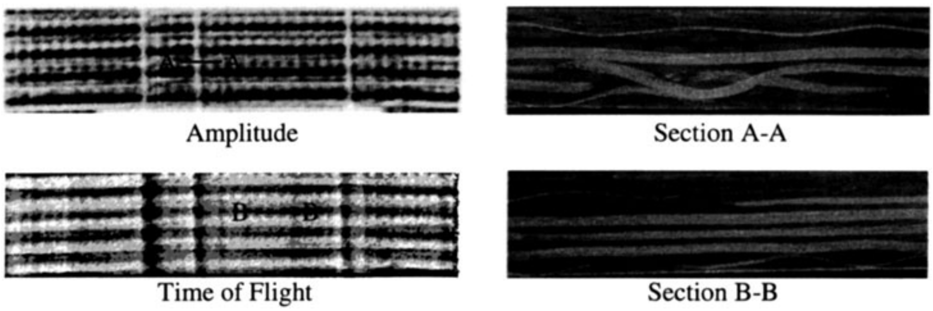


Figure 8. Seemingly severe flaws can be attributed to fiber architecture distortion.

FABRICATION OF IDEALIZED 2D TEXTILES

Fabrication methods have been developed and demonstrated to be effective for producing two dimensional samples which represent idealized textile architectures. These architectures can be tailored to exhibit specific details seen in 3D textile architecture. The details of the fabrication methods will not be addressed here, but are discussed in depth in references 6 and 7. Representative samples fabricated using these methods are shown in Figure 9. Note that control over stacking of undulations and spacing of undulations allows for textile architecture similar in many ways to 3D textile architecture.

INSPECTION -- 2D IDEALIZED

It has been determined that a knowledge of the actual fiber architecture may be required to assess the expected mechanical performance of three-dimensional textiles. Towards this end we have investigated the possibilities of imaging the actual architecture through nondestructive means. We showed previously that severe undulations can result in large reductions in signal amplitude due to wave scattering at the ply interface. This is illustrated more clearly in Figure 10, which is a pulse-echo C-scan of the reflected signal from the wavy layer interface. This technique has proven extremely successful for the location of waves, again referring to out-of-plane undulations in fiber architecture, and for the positioning of waves in-plane, but it gives very little information regarding the geometry or through-the-thickness arrangement of the waves. Figure 11 is a similar C-scan for a sample containing two isolated waves. It is clear that a wave exists and that it displays no in-plane misalignment, being aligned with the panel across the specimen. The period (crest

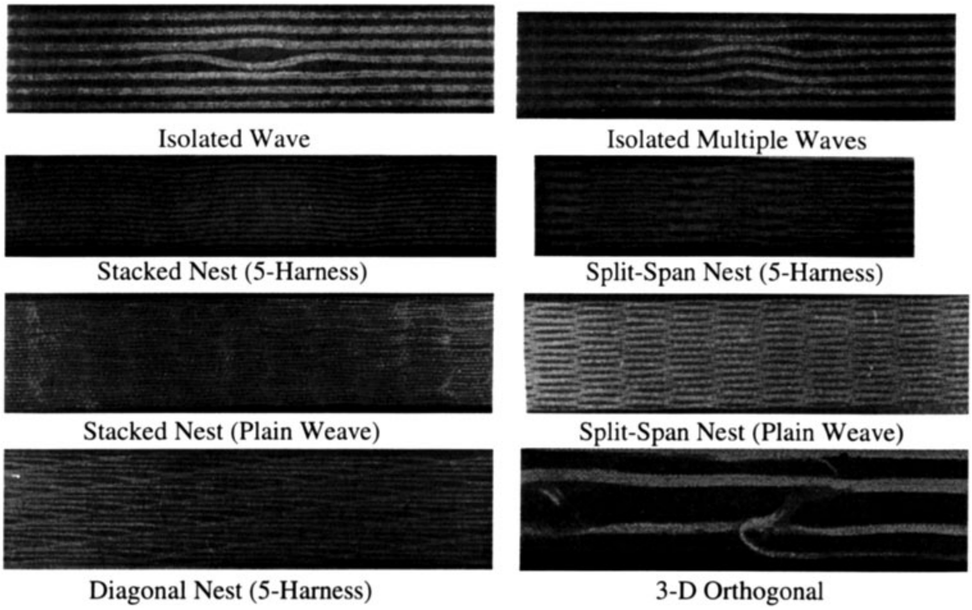


Figure 9. Representative idealized textile composites.

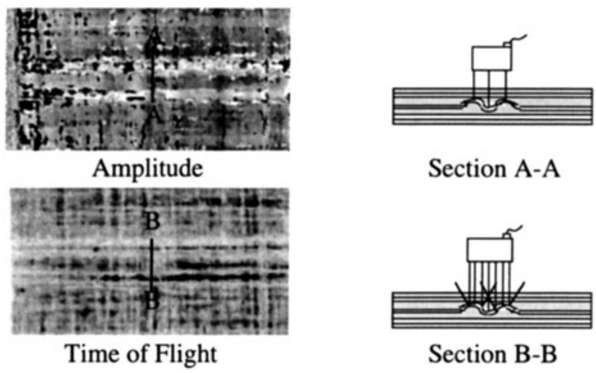


Figure 10. Waves may be identified by scattering of ultrasonic energy on the slopes.

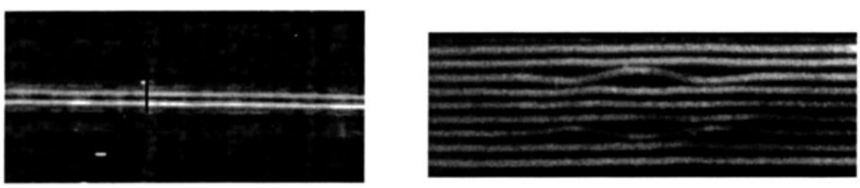


Figure 11. Waves can be located and characterized for position and period.

to crest distance) of the wave is determined by measuring the spacing on the scan. The amplitude (distance the wave distorts from its linear in-plane path) of the wave, however, and the fact that there are actually two waves through-the-thickness eludes us. One could make judgements on the amplitude of the wave based upon a reduction of the signal amplitude in the ascending and descending slopes of the wave compared with that obtained away from the wave. Waves with small amplitudes have shallow slopes and thus deflect less energy than waves with large amplitudes and corresponding higher slopes. This interpretation, however, presupposes that all of the energy is deflected by a single wave, and not in smaller increments across several waves. For this example that is obviously not the case, nor will it be for textile samples.

What is required, then, is a means to image the textile through-the-thickness. We are investigating the use of B-scan images to accomplish this. Work is underway for identifying the optimal combination of frequency, focusing conditions and distance-amplitude correction for imaging such fiber architecture anomalies. Ideally, the result should be an image similar to that shown in Figure 12, which was obtained by the admittedly impractical method of scanning the cut through-the-thickness surface to detect variations in acoustic impedance.

SUMMARY

We have verified the dual signal from the in-plane and out-of-plane reinforcement in 3D orthogonal weaves. A careless investigation which does not isolate these two responses may miss large failed regions, such as the extensive crack in sample 24-PH-4. Transducers of sufficiently high frequency should be used to clearly isolate the two signals and to ensure separate gating. If the frequency is too low or the sample thickness is too small the signals overlap, resulting in the same difficulties as using a single gate. Furthermore, conventional attenuation measurements are not practical for 3D orthogonal weaves due to this separation of incident energy.

Braid, angle interlock and idealized textile samples are inspectable by traditional C-scan and velocity/attenuation methods, however the strong influence of the textile pattern on the C-scan image makes detection of subtle flaws difficult. Unfortunately, unit cell size appears to affect flaw detectability, with composites composed of smaller unit cells being more difficult to inspect. This indicates that inspection methods will depend highly on geometry of the part as well as geometry of the fiber architecture.

If 3D textile composites are to be used in industry, it is believed that some method for assessing actual as-cured fiber architecture needs to be established, such that the expected mechanical performance may be estimated. Mechanical testing of typical 3D textiles and of idealized samples is presently underway in an attempt to correlate strength and stiffness with the degree of architectural distortion. With this information, we will be able to ascertain which features of fiber architecture distortion have the greatest impact on mechanical performance and thus which features should be identified through nondestructive evaluation. It is known, however, that an effective estimation of performance will require a knowledge of the types of fiber architecture distortion, the relative magnitude of the distortion, and the density and relative arrangement of the distortion.

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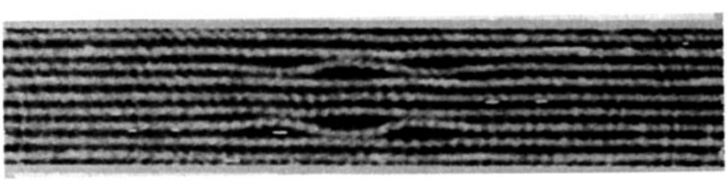

Figure 12. Through-the thickness characterization of fiber architecture is required.

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